Effect of the Gate Tunneling Current on the High-Frequency Noise of MOSFETs

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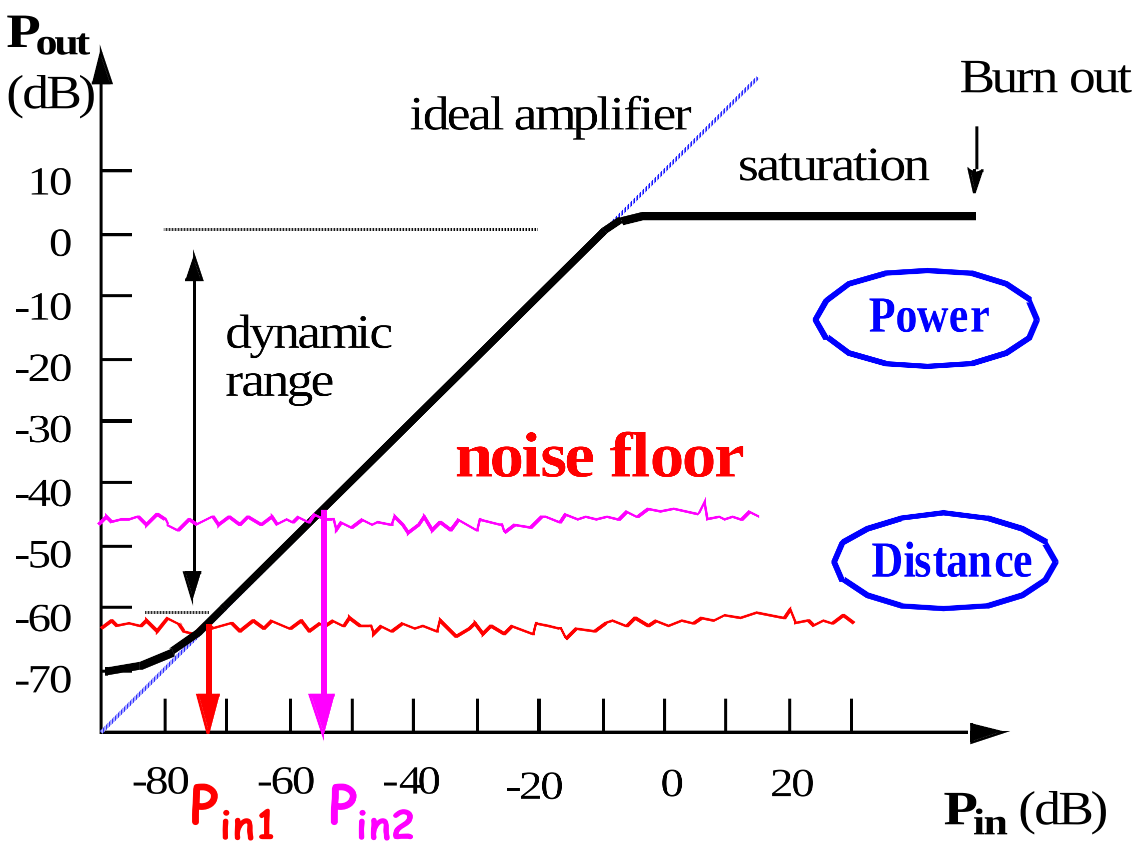
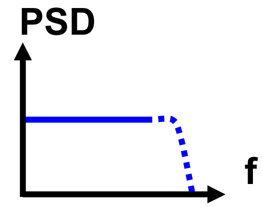
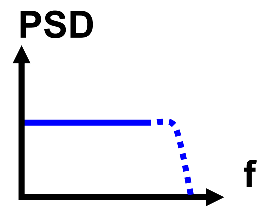
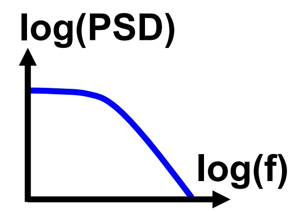
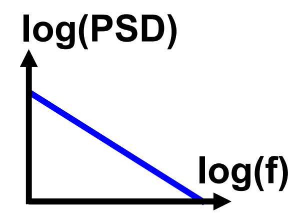
Workshop on Compact Modeling (8-12 May 2005)

Why Does Noise Matter

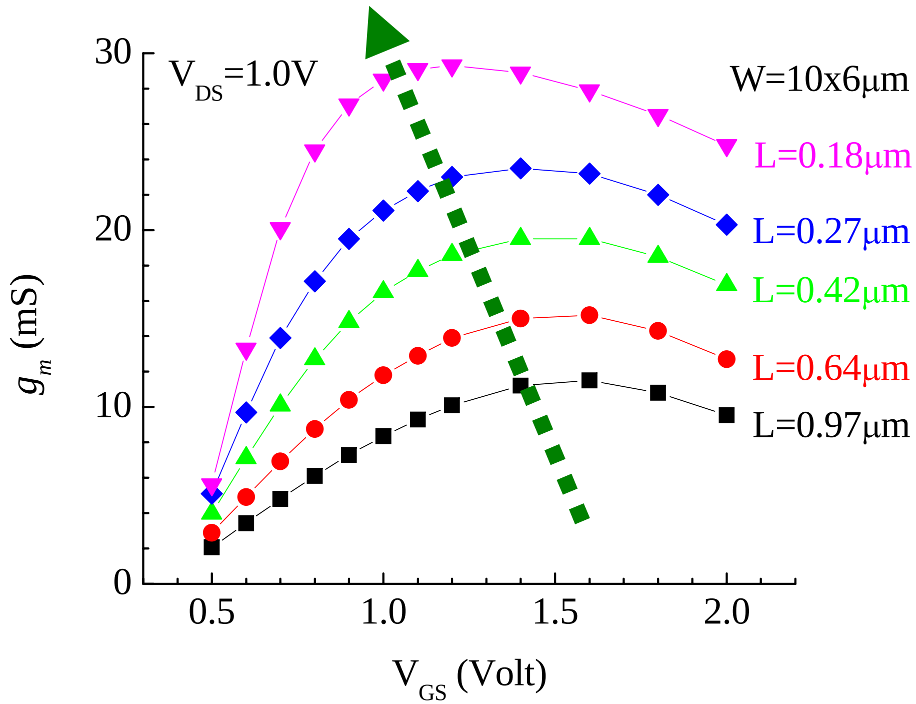


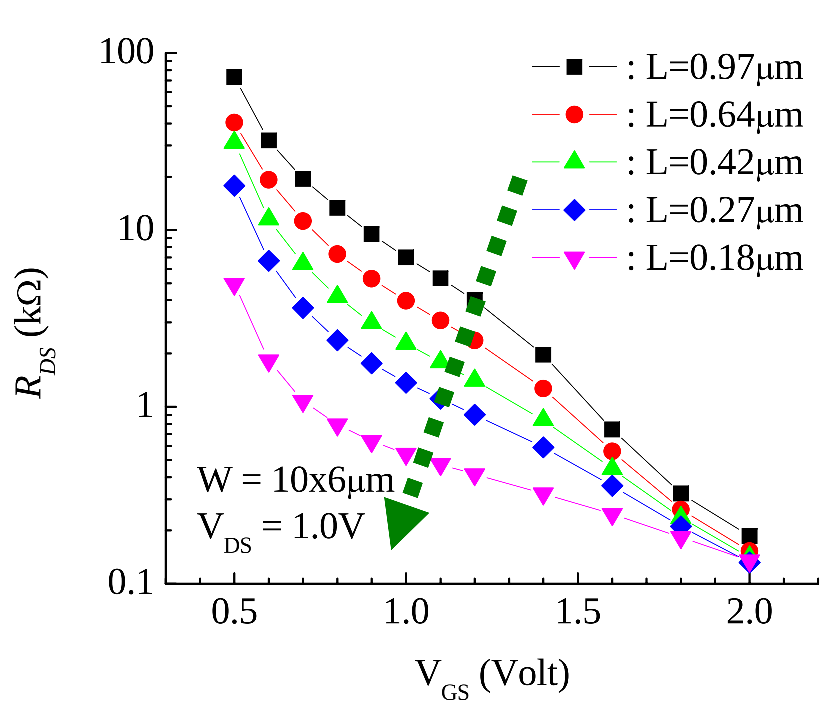
The battery life time and the distance between the wireless components will be limited by the noise floor of the front-end amplifier.

Types of Electrical Noise

Type	Cause	Power Spectral Density	
Thermal (Johnson, Nyquist)	Thermal motion of carriers	$4kT/R$ (white)	
Shot	Discrete carriers crossing a barrier	$2qI$ (white)	
Generation-recombination	Trapping and detrapping of carriers	$\propto \dfrac{\tau}{1+(2\pi f\tau)^2}$ (Lorentzian)	
Flicker (1/f, excess)	Several origins	$\propto 1/f$ (pink)	

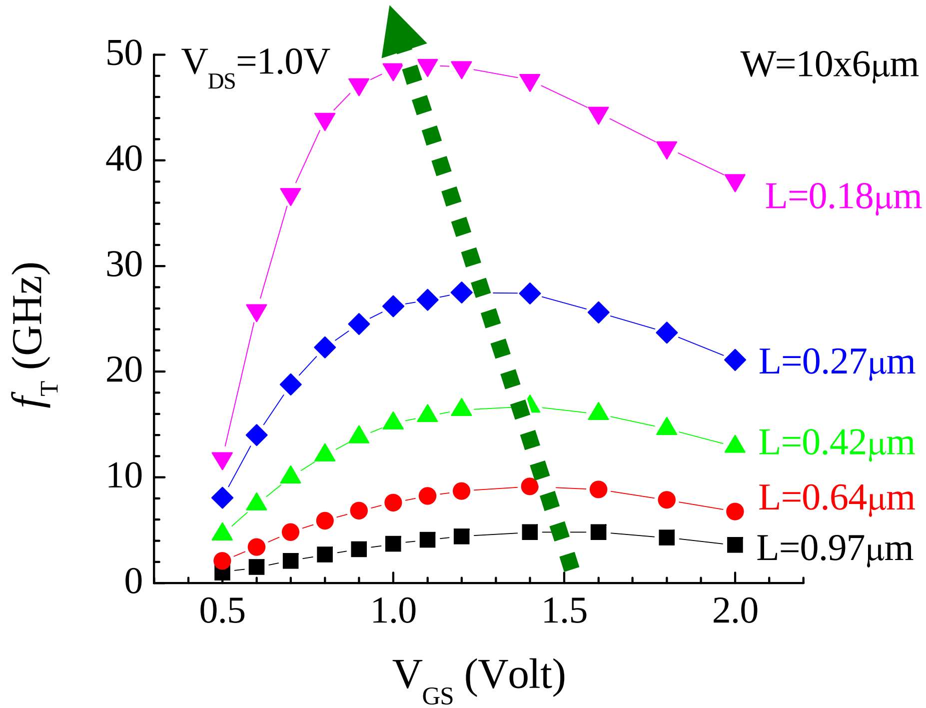
Design Issues - Scaling

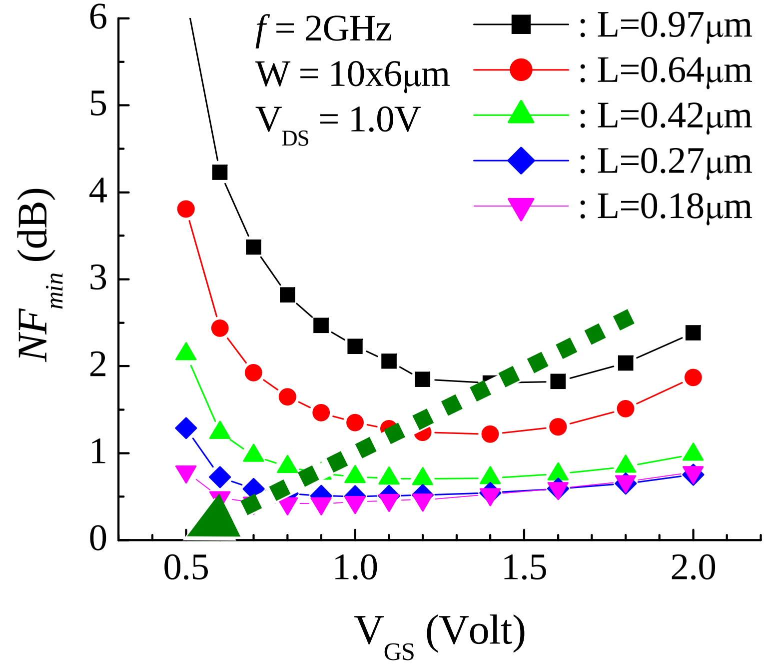




- **Channel length of devices reduced**
  - **Increased g_m and peak value of g_m occurs at lower V_{GS} values**
- **Output resistance decreases with channel length reduction due to channel-length modulation.**

MOSFET RF & Noise Performance



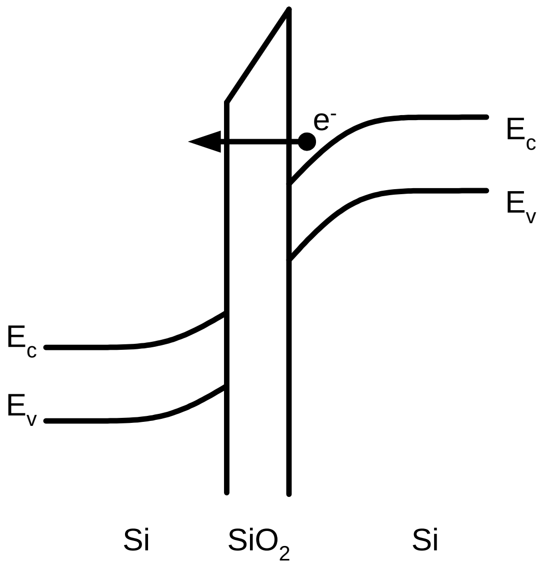


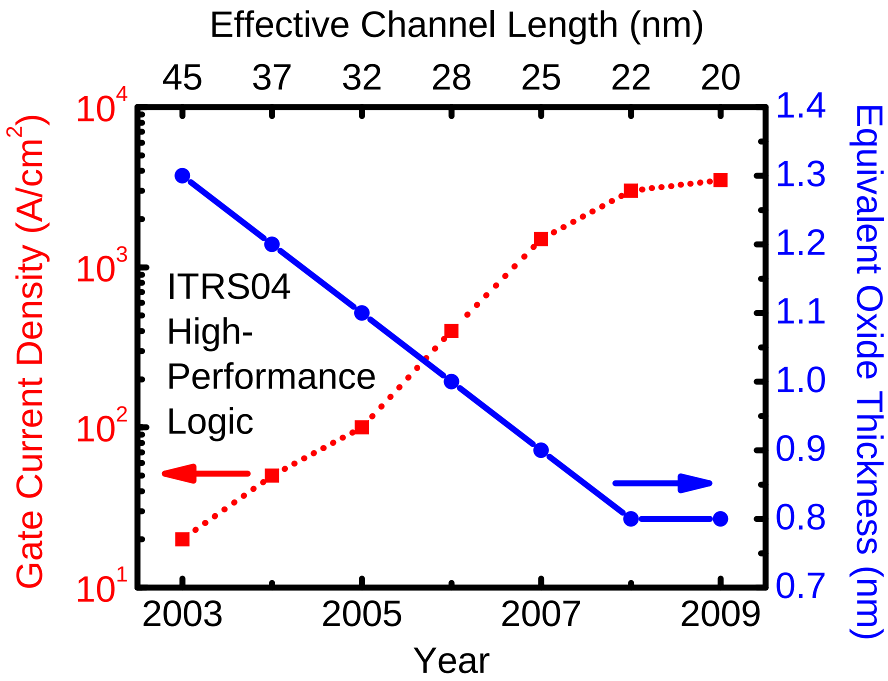
- **The faster increase in g_m results in reduced NF_{min} and the lowest NF_{min} is shifted to lower V_{GS} values**
- **Maximum f_T is around 50 GHz and the best NF_{min} is about 0.5 dB at 2 GHz**

Outline

- MOSFET scaling and gate tunneling current
- Gate current noise
- MOSFET small-signal model with gate current
- Gate current effect on noise parameters
- Scaling and gate current noise
- Gate current noise partition
- Conclusions

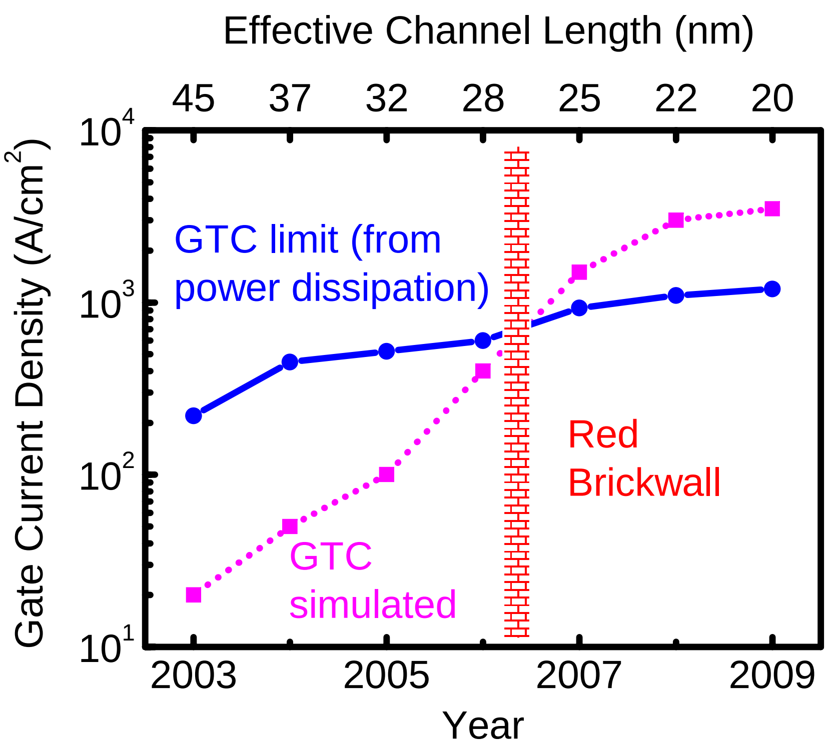
MOSFET Scaling & Gate Current



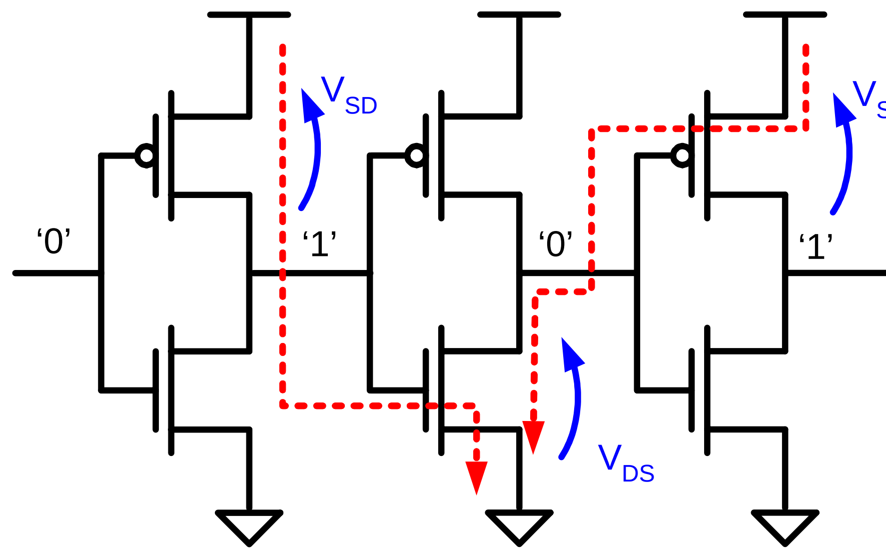


- **MOSFET lateral scaling is accompanied by vertical scaling to control SCE**
- **Carriers can tunnel through the oxide of aggressively scaled MOSFETs.**
- **Significant gate currents are observed for t_{ox} below ~2nm**

Gate Current Effects



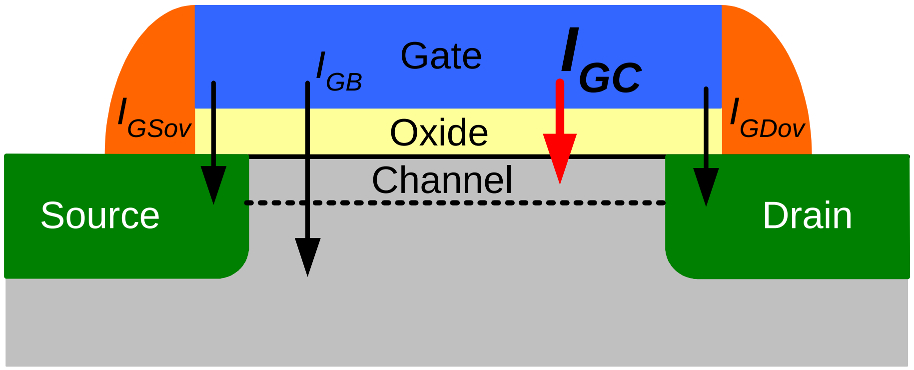
ITRS 2004, High-Performance Logic (HP)

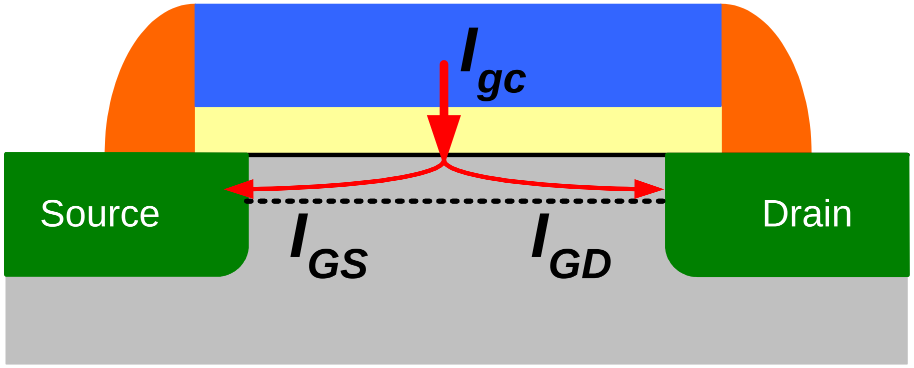


- **Gate Tunneling Current (GTC) increases static power dissipation of CMOS digital circuits**
- **It can also affect analog and RF circuit performance**

Gate Current Components

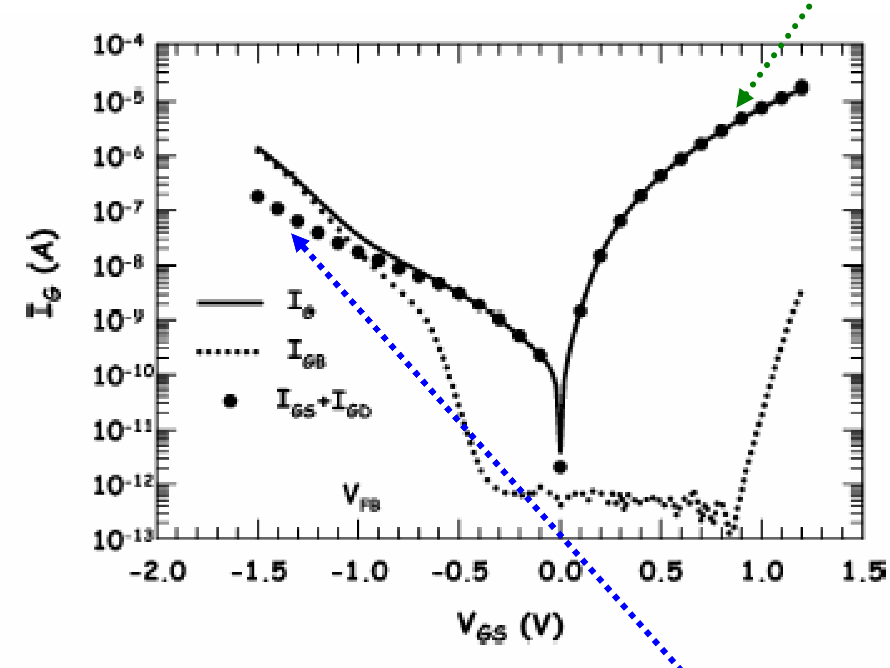
- Three current components
  - Gate-channel (I_{GC})
  - Gate-bulk (I_{GB})
  - Gate-overlap (I_{GSov},I_{GDov})
- Gate-channel component is split between source and drain (I_{GS}, I_{GD})
- Overlap components will become more important in smaller devices

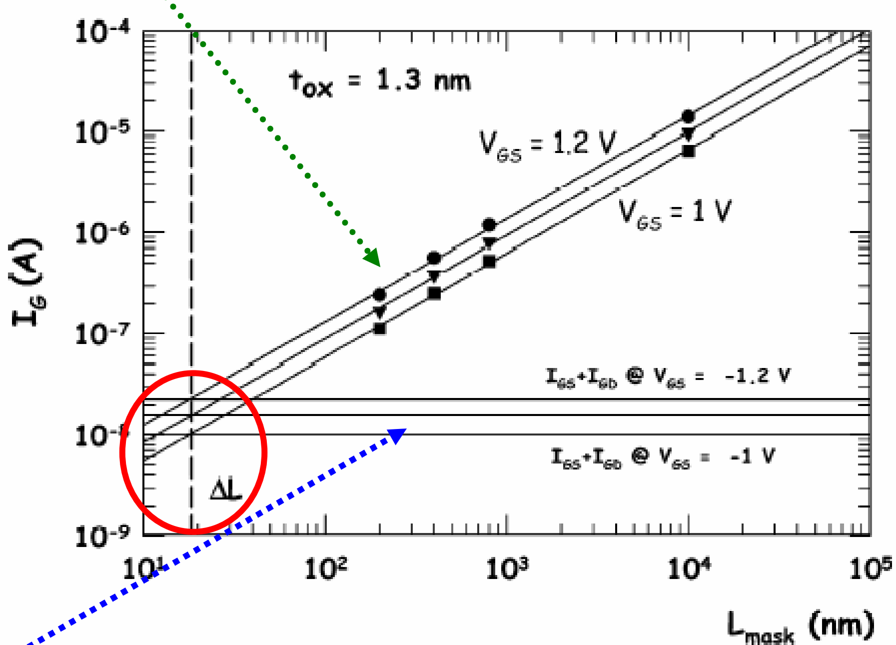




GTC - Channel Length Extraction

$$V_{GS} >> V_T \Rightarrow I_G = J_{GC}W\left(L_{mask} - \Delta L\right) + \left(J_{GSov} + J_{GDov}\right)W\Delta L$$





$$V_{GS} < 0 \Rightarrow I_{GS} + I_{GD} = \left(J_{GSov} + J_{GDov}\right)W\Delta L \qquad I_G = I_{GS} + I_{GD} \Rightarrow \Delta L = L_{mask}$$

- **Conventional methods for parameter extraction (C-V) are difficult to apply to MOSFETs with GTC**
- **GTC can be used to extract the effective channel length**

Marin et al., IEEE EDL, vol. 25, no. 4, p. 202, April 2004.

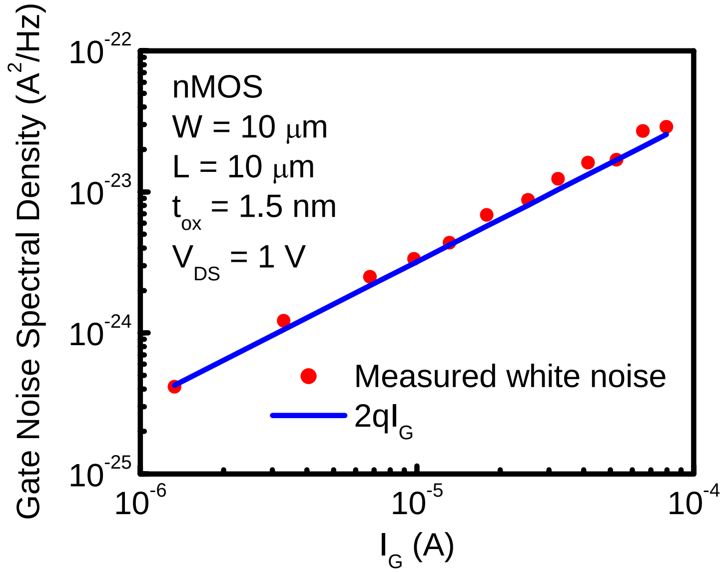
Gate Current Noise

- **Gate current is caused by discrete carriers randomly crossing a potential barrier ➔ Shot noise, proportional to current**

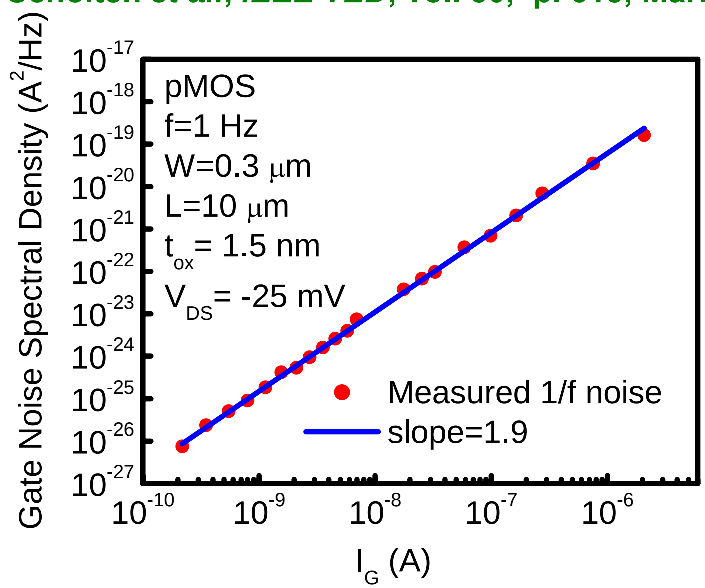
$$S_{I_G} = 2qI_G$$

- **Also 1/f or flicker noise, detailed microscopic origin still under discussion**

$$S_{I_G} \propto \frac{I_G{}^2}{f}$$

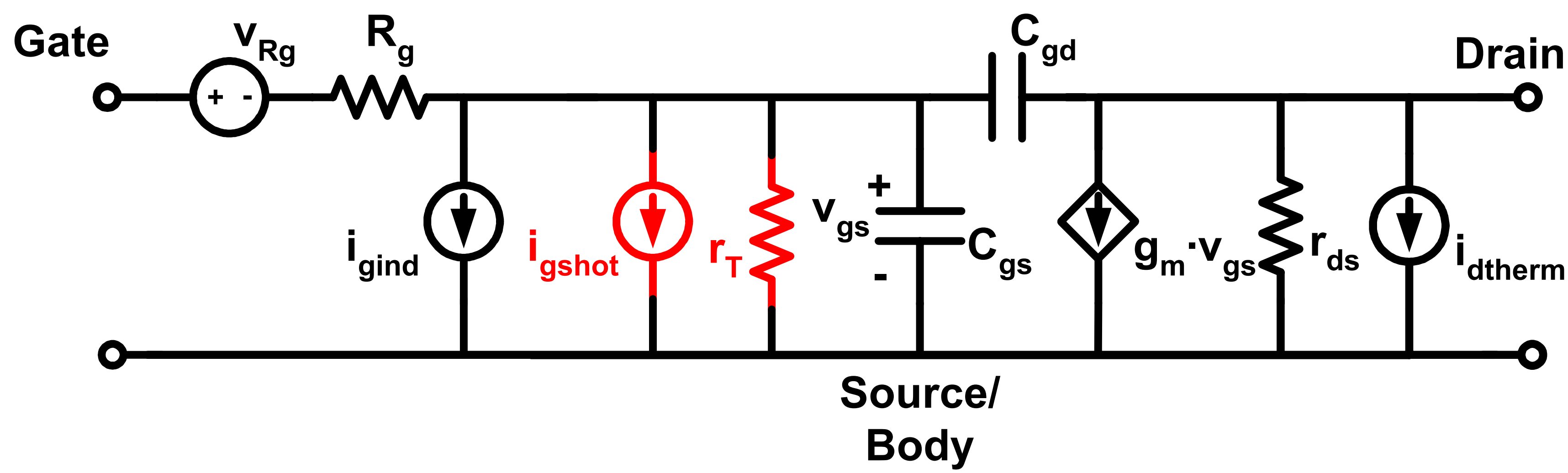


Scholten *et al.*, *IEEE TED*, vol. 50, p. 618, Mar. 2003



Valenza *et al.*, *IEE Proc. G*, vol. 151, p. 102, Apr. 2004

MOSFET Small-Signal Modeling



- Two additional elements: gate current noise source and gate-source incremental resistance
- For gate current, considers only I_{GS} (gate-channel source component)
- Model valid at low and moderate frequencies (where GTC effect is more significant)

Gate Current and Resistance

$$J_G = \frac{q^3}{16\pi^2\hbar\phi_b}\left(\frac{V_G}{t_{ox}}\right)^2 \exp\left\{-\frac{4}{3}\frac{\sqrt{2m_{ox}}\phi_b^{3/2}}{\hbar q}\frac{t_{ox}}{V_G}\left[1-\left(1-\frac{qV_G}{\phi_b}\right)^{3/2}\right]\right\}$$

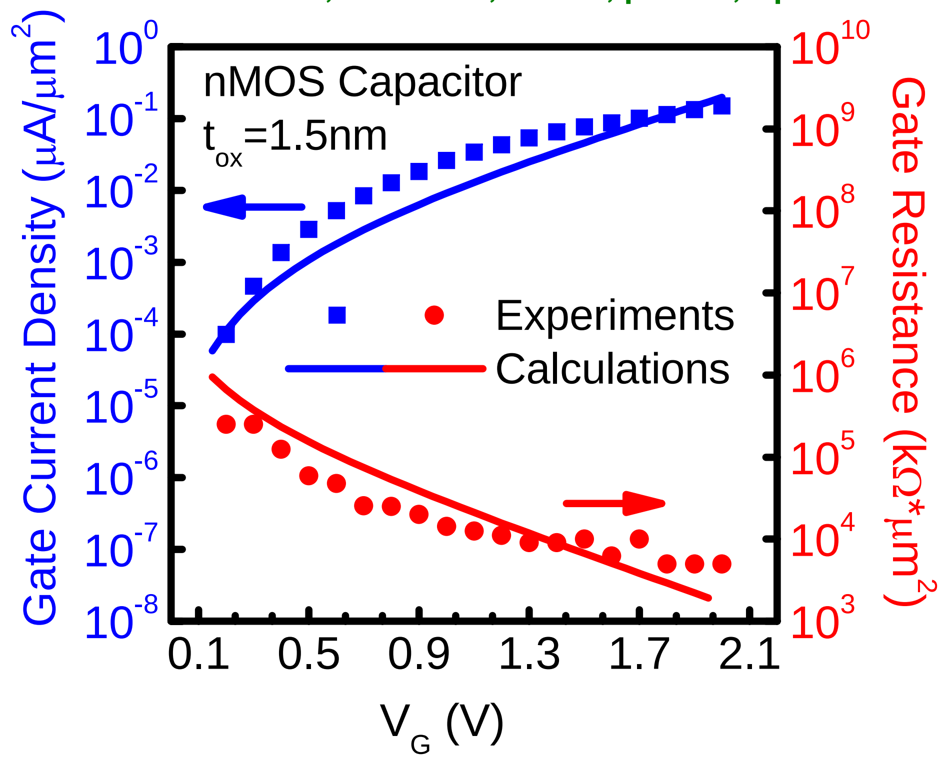
Direct tunneling through a trapezoidal barrier

Schuegraf and Hu, IEEE TED, vol. 41, p. 761, May 1994

$$r_T = \left(\frac{\partial I_G}{\partial V_G}\right)^{-1} \qquad \phi_b \approx 3.1\,\text{eV};\ m_{ox} \approx 0.5 m_e$$

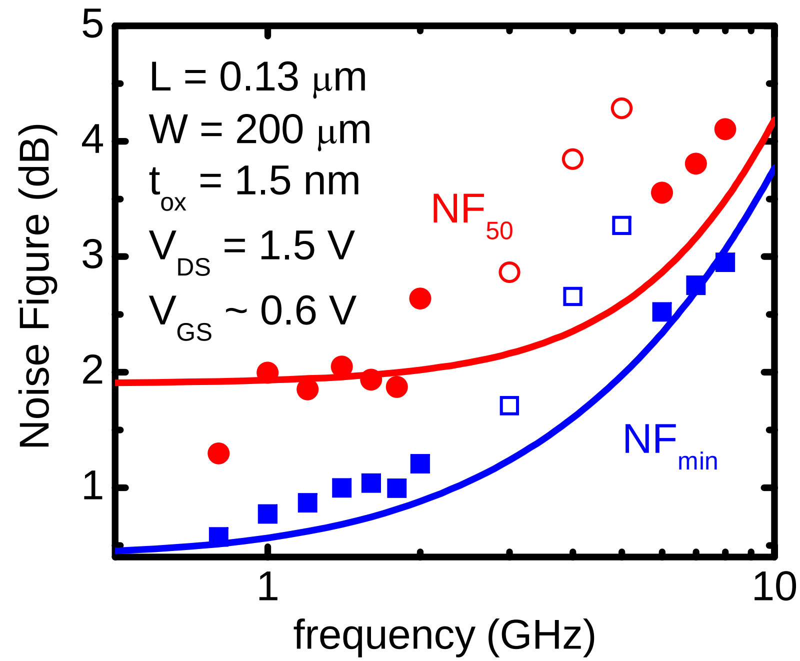
- **Approximate analytical model for direct tunneling**
- **Used to validate and extrapolate experimental data**

Experimental data from: Momose et al., IEEE TED, vol. 50, p. 1001, Apr. 2003



Small-Signal Model Verification

- Very few published experimental data for HF noise with GTC
- Purpose: to verify the small-signal model at low and moderate frequencies
- Small-signal parameters estimated from geometry and biasing



Experimental data from:
H.S. Momose et al., VLSI '98, p. 96, June 1998

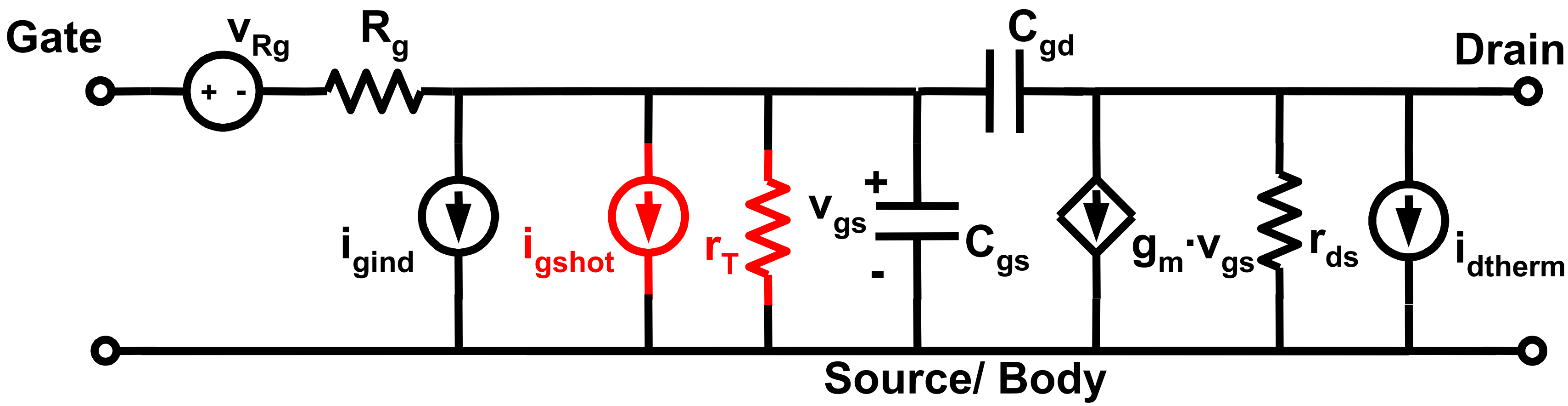
C_{gs} (fF)	C_{gd} (fF)	g_m (mS)	R_g (Ω)	r_T (kΩ)	I_g (μA)	S_{id} (A^2/Hz)	S_{igi} (A^2/Hz)
360	115	160	10	190	4.2	5.1×10^{-21}	2.5×10^{-23} @10GHz

Noise Parameters

$$NF = NF_{min} + \frac{R_n}{G_S} \cdot \left[\left(G_S - G_{S,\,OPT} \right)^2 + \left(B_S - B_{S,\,OPT} \right)^2 \right]$$

- NF_{min} = minimum noise figure
- R_n = equivalent noise resistance
- $G_{S,OPT}$ = optimal value of G_S
- $B_{S,OPT}$ =optimal value of B_S
- G_S = source conductance
- B_S = source susceptance

Noise Parameters and GTC



- Simple analytical expressions
- Based on ss model
- Low and medium freq. range
- Insight into the effect of GTC

$$R_n \approx R_g + \frac{S_{id}}{4kTg_m^2} + R_g^2 \frac{S_{ig}}{4kT} \qquad B_{opt} \approx -\left(\frac{f}{f_{to}}\right)\frac{S_{id}}{4kTg_m R_n} \qquad f_{to} \equiv \frac{g_m}{2\pi\left(C_{gs}+C_{gd}\right)}$$

$$G_{opt} \approx \sqrt{\frac{S_{ig}}{4kTR_n} + \left[\left(\frac{f}{f_{to}}\right)^2 + \frac{1}{(r_T g_m)^2}\right]\frac{S_{id}}{4kTR_n} - B_{opt}^2}$$

$$NF_{min} \approx 1 + 2R_n G_{opt} + \frac{R_g S_{ig}}{2kT} + \left[\left(\frac{f}{f_{to}}\right)^2 + \frac{1}{R_g r_T g_m^2}\right]\frac{R_g S_{id}}{2kT}$$

Conditions :

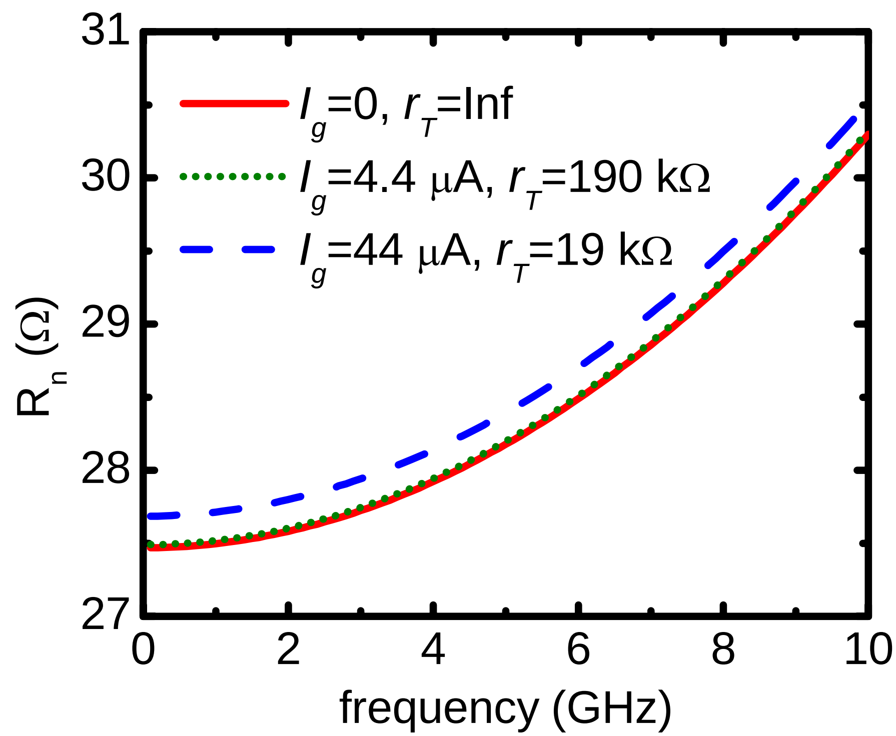
$R_g << r_T$

$\omega C_{gd} << g_m$

$\omega R_g(C_{gs} + C_{gd}) << 1$

Noise Parameters and GTC: R_n

- **Noise resistance is dominated by gate resistance and channel noise at all frequencies**
- **This trend will likely continue even with further downscaling**

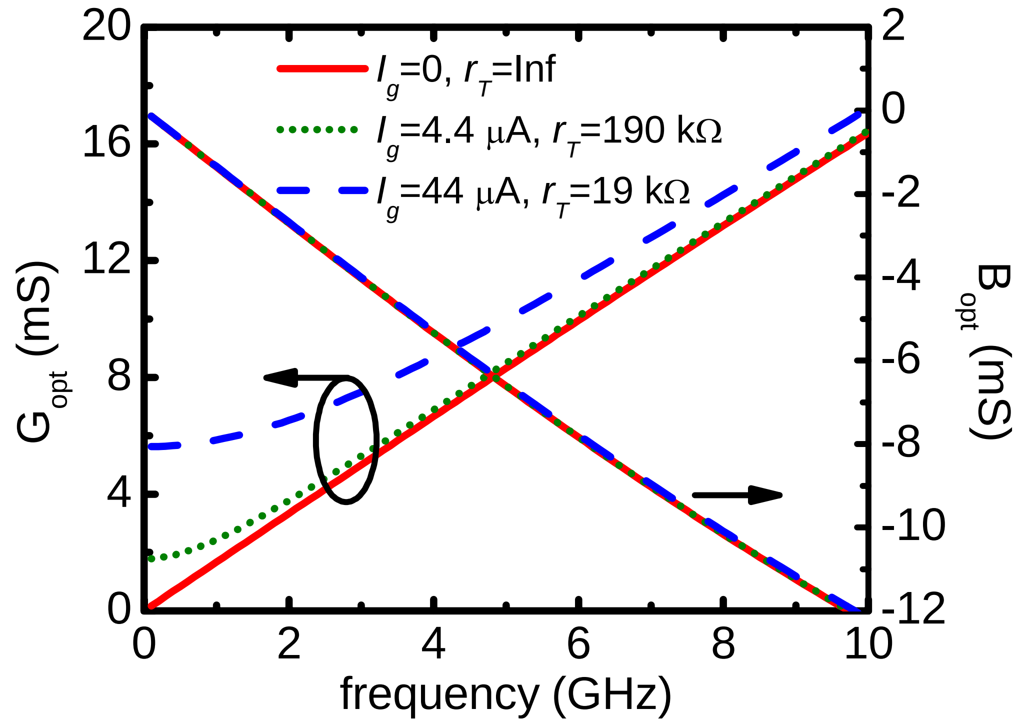


$$R_n \approx R_g + \frac{S_{id}}{4kTg_m^2} + R_g^2 \frac{S_{ig}}{4kT}$$

Dominant terms

Noise Parameters and GTC: Y_{opt}

- G_{opt} changes with GTC noise, especially at relatively low frequencies
- The frequencies at which G_{opt} is most affected can shift well into GHz range with scaling
- Effect on B_{opt} is very small
- r_T important only at VLF

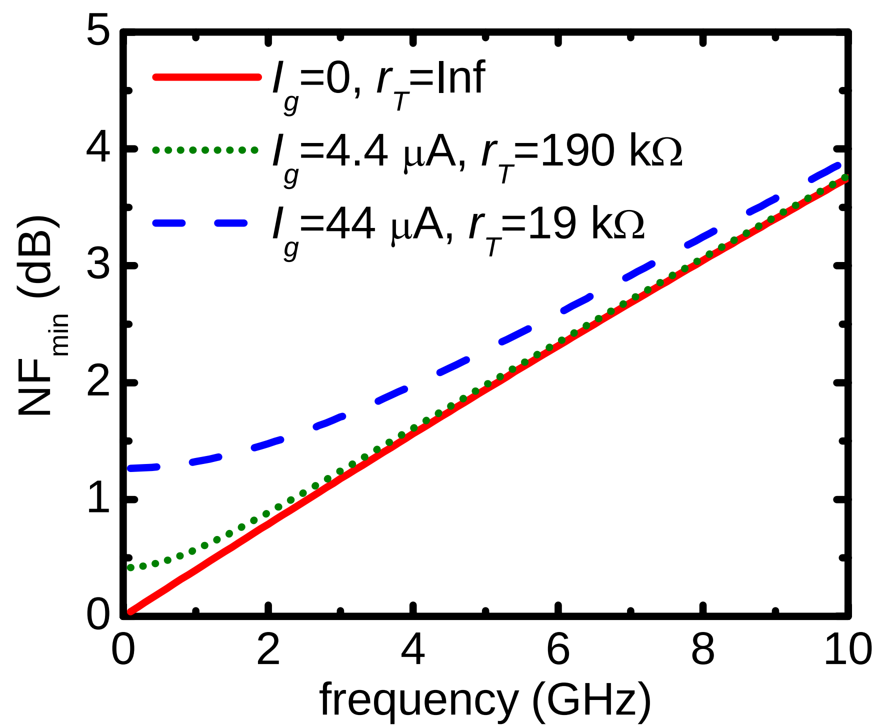


$$G_{opt} \approx \sqrt{\frac{S_{ig}}{4kTR_n} + \left[\left(\frac{f}{f_{to}}\right)^2 + \frac{1}{\left(r_T g_m\right)^2}\right]\frac{S_{id}}{4kTR_n} - B_{opt}^2}$$

$$B_{opt} \approx -\left(\frac{f}{f_{to}}\right)\frac{S_{id}}{4kTg_m R_n} \qquad f_{to} \equiv \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)}$$

NF_{min} and GTC

- Like G_{opt}, NF_{min} changes with GTC noise, especially at relatively low frequencies
- The frequencies at which NF_{min} is most affected can shift well into GHz range with scaling
- Tunneling resistance important only at VLF



$$NF_{min} \approx 1 + 2R_n G_{opt} + \frac{R_g S_{ig}}{2kT} + \left[\left(\frac{f}{f_{to}} \right)^2 + \frac{1}{R_g r_T g_m^2} \right] \frac{R_g S_{id}}{2kT}$$

Most affected by GTC noise

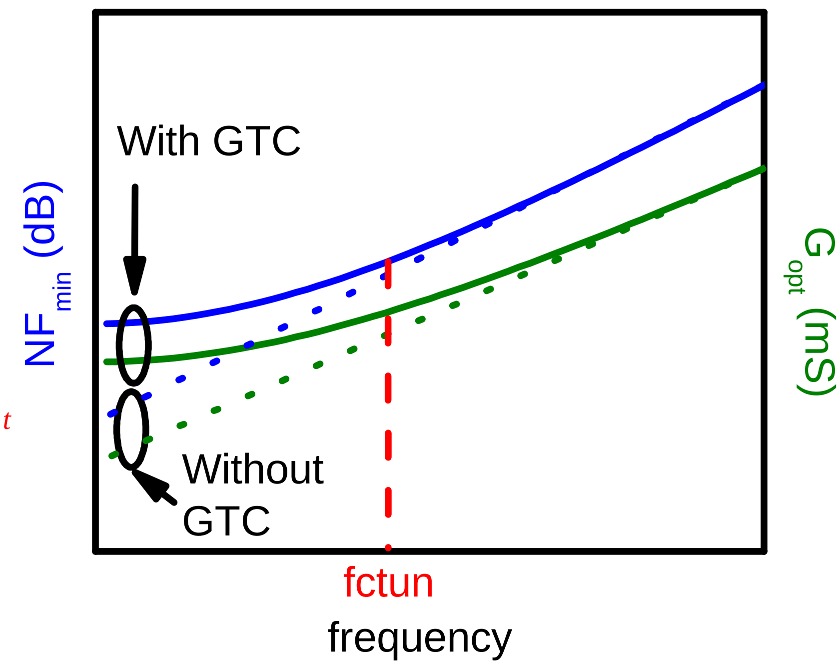
A GTC Noise Figure of Merit

- f_{ctun} is the frequency where GTC contributes as much noise as the channel thermal noise
- It gives a measure of the frequencies at which the noise from GTC is important

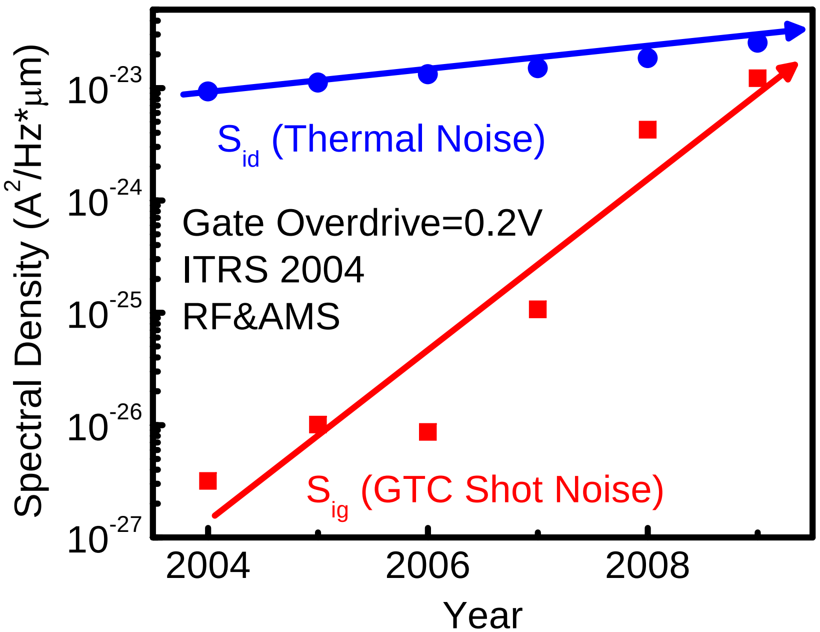
$$G_{opt} \approx \sqrt{\frac{S_{ig}}{4kTR_n} + \left(\frac{f}{f_{to}}\right)^2 \frac{S_{id}}{4kTR_n} - B_{opt}^2}$$

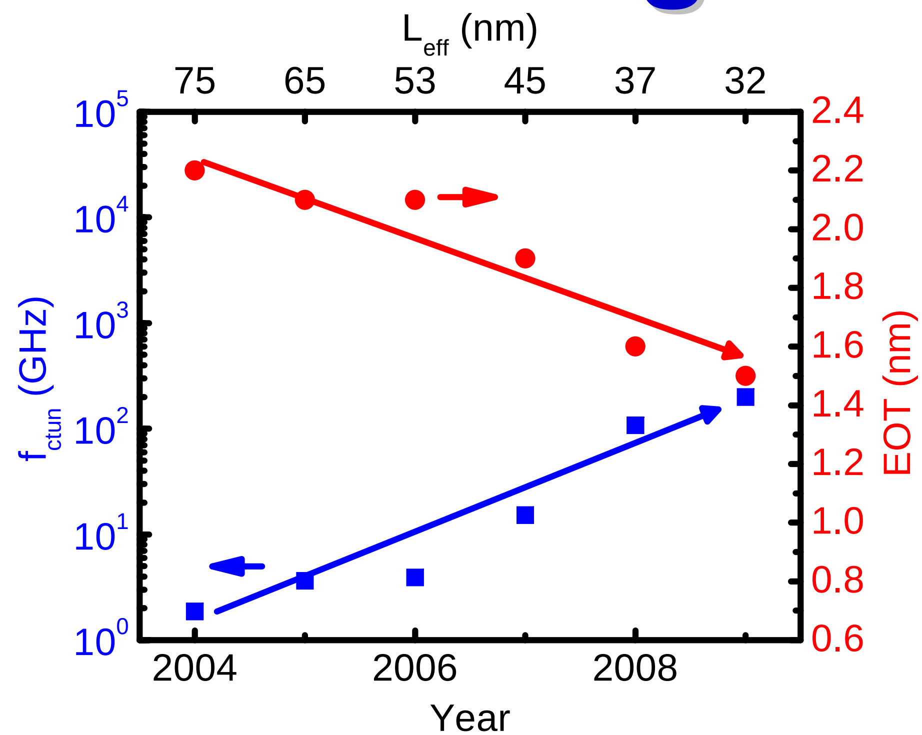
$$NF_{min} \approx 1 + \frac{R_g S_{ig}}{2kT} + \left(\frac{f}{f_{to}}\right)^2 \frac{R_g S_{id}}{2kT} + 2R_n G_{opt}$$

$$f_{ctun} \approx f_{to}\sqrt{\frac{S_{ig}}{S_{id}}}$$



GTC Noise: ITRS Scaling





- **S_{ig} increases much faster than S_{id} with scaling**
- **Effect of GTC shifts well into the GHz range**

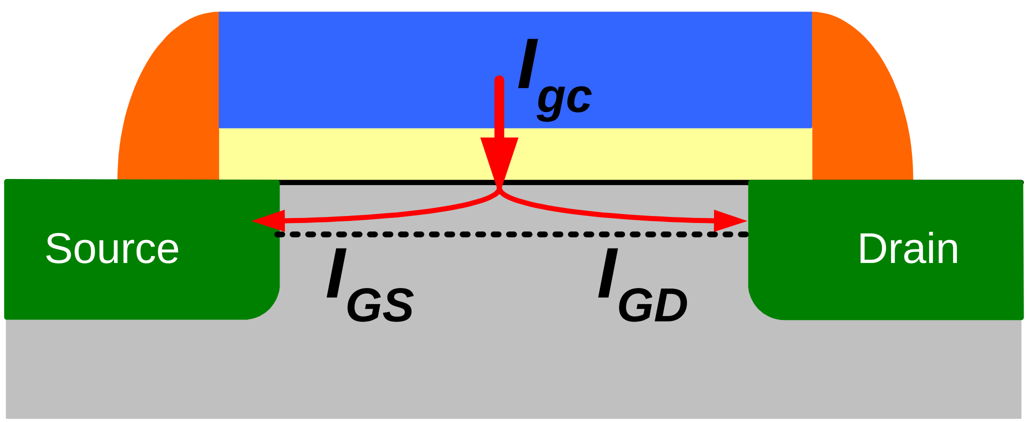
$$S_{id} = 4kT\alpha I_D \frac{4V_{GT}^2 + V_0^2 - 2V_0V_{GT}}{3V_{GT}^2(V_{GT} - V_0)} \qquad V_0 = I_D / WC_{ox}v_{sat}$$

Scaling model from: http://public.itrs.net/Files/2003ITRS/Models.htm

Thermal noise model from Asgaran, Deen and Chen, IEEE TED, vol. 51, no.12, p. 2109, Dec. 2004

GTC Noise Partition

- In the above calculations, gate-drain component of GTC (I_{GD}) was neglected
- How realistic is this?
  - DC value of I_{GD}?
  - Effect of gate current noise on drain current noise?
  - Correlation between gate and drain currents?



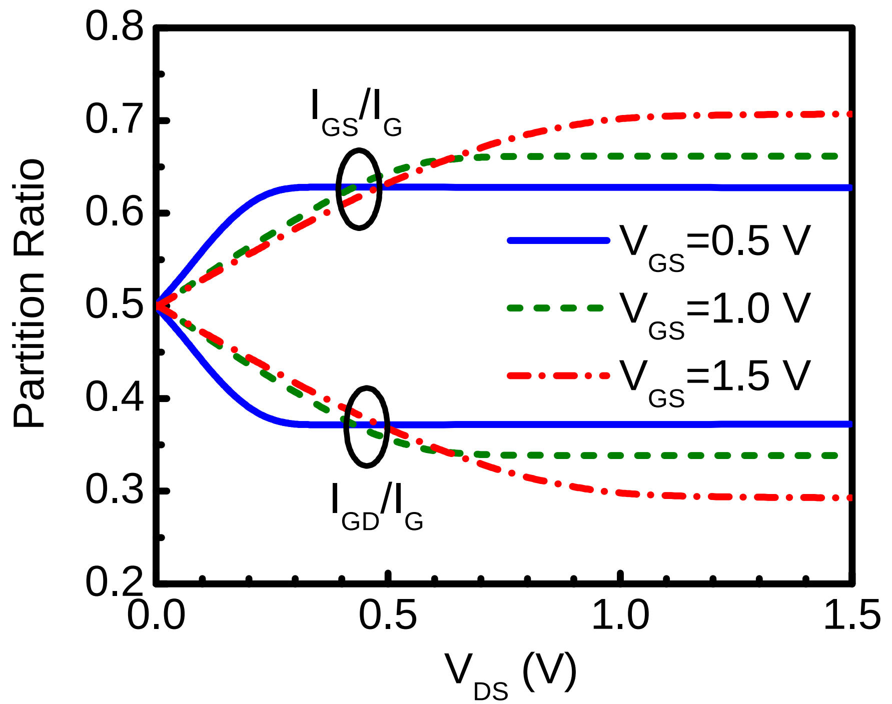
GTC Partition

$$I_{GC} = W\int_0^L J_G(x)\ dx$$

$$I_{GD} = W\int_0^L J_G(x)\left(\frac{x}{L}\right)dx$$

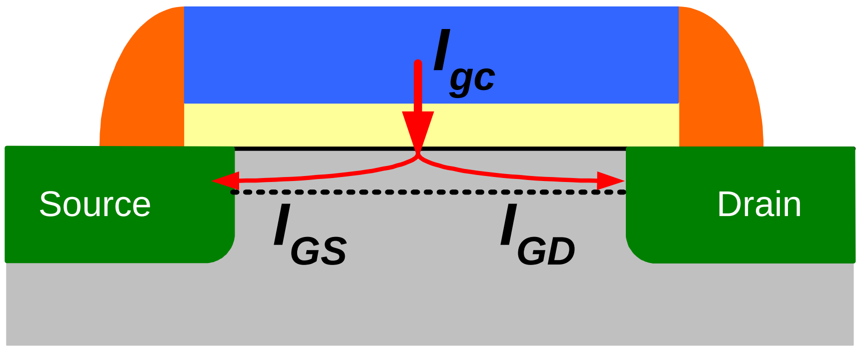
$$I_{GS} = W\int_0^L J_G(x)\left(1-\frac{x}{L}\right)dx$$

R. van Langevelde et al., IEDM '01, p. 289
and
W.K. Shih et al., IEDM '01, p. 293

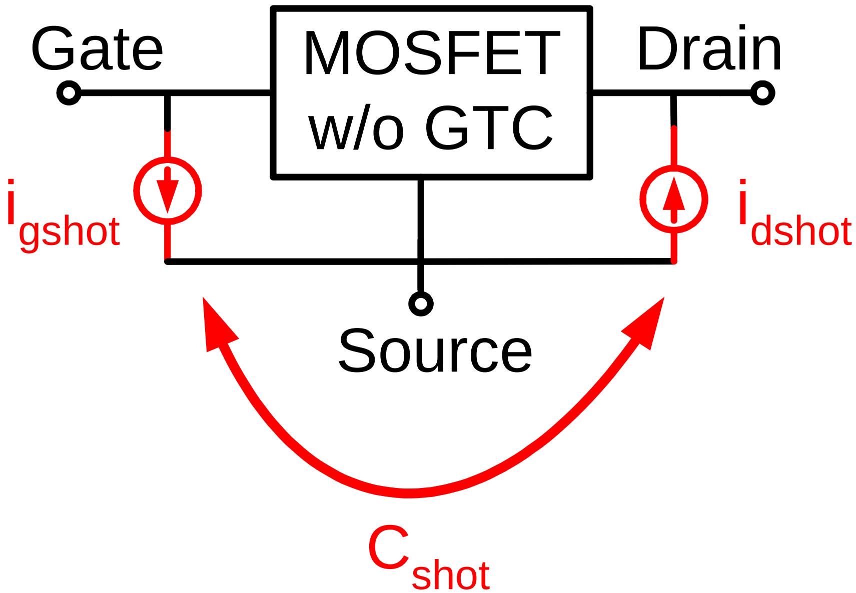


X. Gu et al., IEEE TED, vol. 51, no. 1, p. 127, Jan. 2004

- **The drain component is typically 30%-35% of the total gate current in saturation**



G-D and G-S Shot Noise



$$C_{shot} \approx 0.8$$

$$S_{i_{gshot}} = 2qI_G$$

$$0.15 < \frac{S_{i_{dshot}}}{S_{i_{gshot}}} < 0.3$$

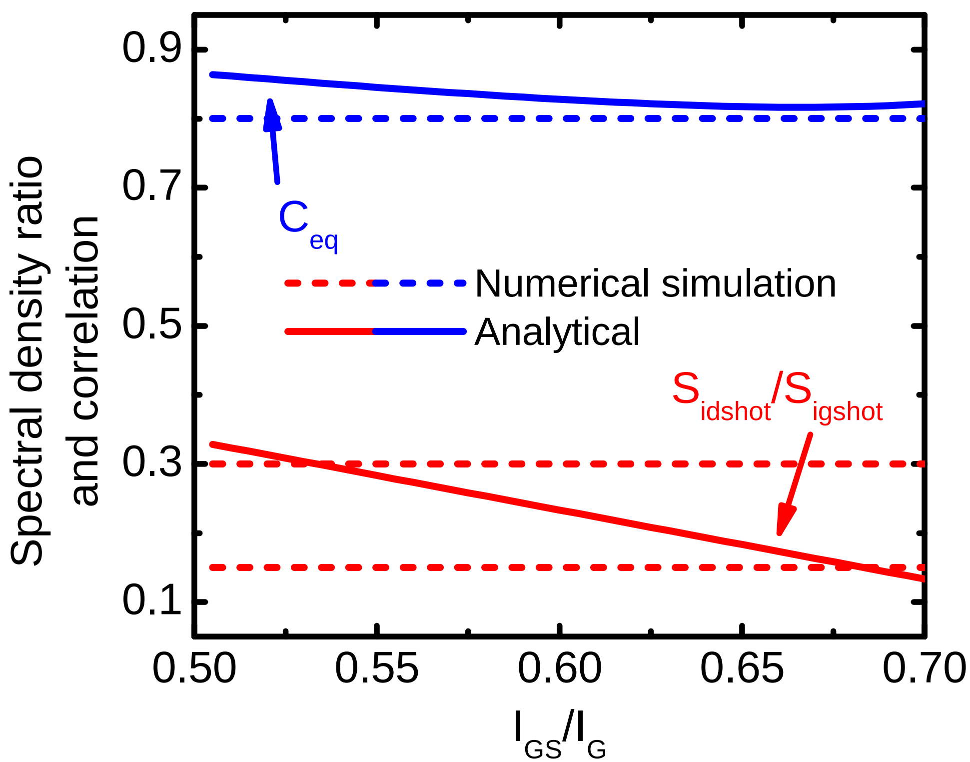
G. Paillончy et al., 2004 IEEE SOI Conf., p. 55

- The gate-drain and gate-source noise currents are correlated (C~0.8)
- The drain-source current noise is less than ~30% of the gate-source current noise
- Not clear what is the bias dependence of the drain shot noise component

Modeling - Noise Partition

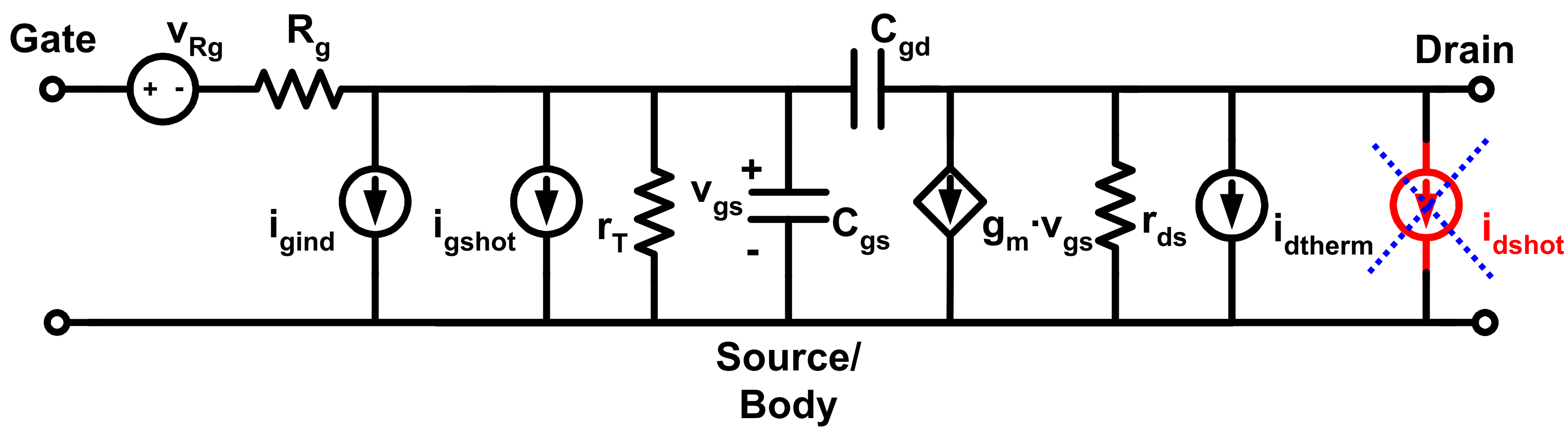
- Analytical formulas for shot noise partition and correlation
- Based on standard gate current partition
- Assumes linear dependence of gate current density with position in the channel
- Results are consistent with numerical simulation

$$\frac{S_{i_{dshot}}}{S_{i_{gshot}}} = \left(\frac{5}{6} - \frac{I_{GS}}{I_G}\right) \qquad C_{shot} = \frac{1 - {I_{GS}}/{I_G}}{\sqrt{{5}/{6} - {I_{GS}}/{I_G}}}$$



Numerical simulation from:
G. Paillon cy et al., 2004 IEEE SOI Conf., p. 55

Drain Shot Noise



$$\frac{I_{GS}}{I_G} = 0.7;\ I_G = 4\mu A;\ S_{idtherm} = 5\times 10^{-21}\ \frac{\mathrm{A}^2}{\mathrm{Hz}} \Rightarrow S_{i_{dshot}} \approx 3\times 10^{-5} S_{idtherm}$$

- Drain shot noise ~ 30%-15% of gate shot noise noise in saturation
- Channel thermal noise dominates over drain shot noise
- Correlation between total gate noise and total drain noise is very small

Conclusions

- The effect of GTC on the noise parameters is more significant at lower frequencies
- For real devices (with gate resistance) noise resistance is affected very little by GTC
- Minimum noise figure and optimum source conductance are the most affected parameters
- With further scaling, the frequencies at which GTC noise is important shifts well into GHz range
- Gate-drain component of GTC noise is limited to ~ 30% of total GTC noise